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Muon $g - 2$ in the MSSM constrained by simple SO(10) SUSY GUT

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Abstract

We show that the best fits of the MSSM constrained by a simple SO(10) SUSY GUT are consistent with the present data on the muon anomalous magnetic moment. The best fits assume rather large values of $\tan\beta \approx 50$, and in our analysis they are not *a priori* correlated in any way, directly or indirectly, with the experimental limit on a_μ . Regions in the SUSY parameter space, which are currently ruled out because of too large a_μ^{SUSY} , are already excluded in the global fit by excessive corrections to m_b , unacceptable $BR(b \rightarrow s\gamma)$, or direct experimental limits on sparticle masses. However, our results indicate that the accuracy expected in the ongoing E821 experiment at BNL will eventually turn the muon anomalous magnetic moment into a major constraint for this regime of the MSSM.

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1 Introduction

The anomalous magnetic moment of the muon, $a_\mu \equiv (g_\mu - 2)/2$, is potentially a significant constraint for any extension of the Standard Model (SM). The measured value quoted by the Particle Data Group [1] is

$$a_\mu^{PDG} = (11\,659\,230 \pm 84) \times 10^{-10}. \quad (1)$$

This value does not take into account the early results ¹ from the E821 experiment at BNL [2, 3]

$$a_\mu^{BNL\,97} = (11\,659\,250 \pm 150) \times 10^{-10}, \quad (2)$$

$$a_\mu^{BNL\,98} = (11\,659\,191 \pm 59) \times 10^{-10}. \quad (3)$$

On the other hand, the SM prediction yields ([4] and references therein)

$$a_\mu^{SM} = (11\,659\,159.6 \pm 6.7) \times 10^{-10}, \quad (4)$$

where the QED, electroweak and hadronic contributions are summed and the errors are combined in quadrature. When we take into account all these results, contributions from new physics beyond the SM are constrained to fit within the window

$$-28 \times 10^{-10} < \delta a_\mu^{NEW} < +124 \times 10^{-10}, \text{ at } 90\% \text{ C.L.} \quad (5)$$

The width of the window is at present dominated by the experimental uncertainty. That, however, will change after the E821 experiment is completed. The inclusion of the current BNL data already reduces the available window by a factor of 2. After two more years of running the E821 is eventually expected to reach the accuracy $\pm 3 \times 10^{-10}$. If the measured central value then turns out to be exactly equal to the SM prediction, eq.(4), the new constraint will be

$$-12 \times 10^{-10} < \delta a_\mu^{NEW} < +12 \times 10^{-10}, \text{ at } 90\% \text{ C.L.}, \quad (6)$$

with the window for new physics narrowed by more than a factor of 6. ²

In the MSSM, there are significant contributions from new physics due to the chargino-sneutrino and neutralino-smuon loops:

$$\delta a_\mu^{\chi^+} = \frac{1}{8\pi^2} \sum_{A\alpha} \frac{m_\mu^2}{m_{\tilde{\nu}_\alpha}^2} \left[(|C_{A\alpha}^L|^2 + |C_{A\alpha}^R|^2) F_1(x_{A\alpha}) + \frac{m_{\chi_A^+}}{m_\mu} \text{Re}\{C_{A\alpha}^L C_{A\alpha}^{R*}\} F_3(x_{A\alpha}) \right], \quad (7)$$

$$\delta a_\mu^{\chi^0} = -\frac{1}{8\pi^2} \sum_{a\alpha} \frac{m_\mu^2}{m_{\tilde{\mu}_\alpha}^2} \left[(|N_{a\alpha}^L|^2 + |N_{a\alpha}^R|^2) F_2(x_{a\alpha}) + \frac{m_{\chi_a^0}}{m_\mu} \text{Re}\{N_{a\alpha}^L N_{a\alpha}^{R*}\} F_4(x_{a\alpha}) \right], \quad (8)$$

¹The 1998 result is still preliminary.

²This estimate does not take into account possible improvements over time in the hadronic uncertainty, and thus the constraint on new physics may actually be even tighter.

where $x_{A\alpha} = m_{\chi_A^+}^2/m_{\tilde{\nu}_\alpha}^2$, $x_{a\alpha} = m_{\chi_a^0}^2/m_{\tilde{\mu}_\alpha}^2$,

$$\begin{aligned} C_{A\alpha}^L &= -g_2 V_{A1} (\Gamma_{\nu L}^\dagger)_{2\alpha}, \\ C_{A\alpha}^R &= +\lambda_\mu U_{A2} (\Gamma_{\nu L}^\dagger)_{2\alpha}, \\ N_{a\alpha}^L &= -\lambda_\mu N_{a3} (\Gamma_{eR}^\dagger)_{2\alpha} + \left(\frac{g_1}{\sqrt{2}}N_{a1} + \frac{g_2}{\sqrt{2}}N_{a2}\right) (\Gamma_{eL}^\dagger)_{2\alpha}, \\ N_{a\alpha}^R &= -\lambda_\mu N_{a3} (\Gamma_{eL}^\dagger)_{2\alpha} - \sqrt{2} g_1 N_{a1} (\Gamma_{eR}^\dagger)_{2\alpha}, \end{aligned} \quad (9)$$

and the standard integrals over the two-dimensional Feynman parameter space are

$$\begin{aligned} F_1(x) &= \frac{1}{12(x-1)^4} (x^3 - 6x^2 + 3x + 2 + 6x \ln x), \\ F_2(x) &= \frac{1}{12(x-1)^4} (2x^3 + 3x^2 - 6x + 1 - 6x^2 \ln x), \\ F_3(x) &= \frac{1}{2(x-1)^3} (x^2 - 4x + 3 + 2 \ln x), \\ F_4(x) &= \frac{1}{2(x-1)^3} (x^2 - 1 - 2x \ln x). \end{aligned} \quad (10)$$

In these relations, notation of [5, 6, 7] is assumed. C 's and N 's are the couplings of the chiral muon states with the charginos and neutralinos, respectively. U_{A2} , V_{A1} and N_{a3} are the elements of the chargino and neutralino mixing matrices, $A = 1, 2$; $a = 1, 4$. Γ 's are the mixing matrices of the sleptons after the flavor eigenstates have been first rotated by the unitary matrices which diagonalize the respective fermionic states. Note that $\alpha = 1, 3$ for sneutrinos and $\alpha = 1, 6$ for charged sleptons. In particular, for the charged sleptons each $(\Gamma_e)_{\alpha i}$ is a 6×3 matrix defined as $(\Gamma_{eL})_{\alpha i} = Z_{\alpha i}$, $(\Gamma_{eR})_{\alpha i} = Z_{\alpha i+3}$, ($i = 1, 3$), where Z is a 6×6 mixing matrix for charged sleptons of all three generations. For 3 sneutrinos, $\Gamma_{\nu L}$ directly diagonalizes the 3×3 sneutrino mass matrix. $m_{\chi_A^+}$, $m_{\chi_a^0}$, $m_{\tilde{\nu}_\alpha}^2$ and $m_{\tilde{\mu}_\alpha}^2$ are the chargino, neutralino, sneutrino and charged slepton mass eigenvalues, m_μ and λ_μ are the muon mass and diagonal muon Yukawa coupling, and g_1 and g_2 are the electroweak gauge couplings.

Note that at first glance the terms proportional to F_3 and F_4 in eqs.(7, 8), respectively, are enhanced by m_χ/m_μ . The net enhancement is actually of the order $v_u/v_d \equiv \tan\beta$. (v_d and v_u are the Higgs vevs which give masses to the d -quarks and charged leptons, and to the u -quarks, respectively.)³ The enhancement by $\tan\beta$ can be traced back to the diagrams with the chirality flip inside the loop (or in one of the vertices) as opposed to the terms proportional to F_1 and F_2 where the chirality flip takes place in the external muon leg. There are no similarly enhanced terms in the SM, where the chirality can only be flipped

³Note that there is no additional enhancement due to $1/\lambda_\mu$ in the terms proportional to F_3 and F_4 after the sum over the mass eigenstates is performed. In fact, any combination of chiral muon states contributes to δa_μ^{SUSY} with the net contribution *suppressed* by small Yukawa coupling λ_μ , as one can see, for instance, from the relevant Feynman diagrams in terms of flavor eigenstates (*i.e.*, in the interaction basis). That also explains why the electron anomalous magnetic moment is less sensitive to new physics than its muon analogy.

in the external muon leg. Thus for $\tan\beta \gg 1$ we expect that the terms proportional to F_3 and F_4 dominate in eqs.(7) and (8), and that compared to the SM electroweak gauge boson contribution δa_μ^{EW} , the SUSY contribution scales approximately as

$$\delta a_\mu^{SUSY} \simeq \delta a_\mu^{EW} \left(\frac{M_W}{\tilde{m}} \right)^2 \tan\beta \simeq 15 \times 10^{-10} \left(\frac{100\text{GeV}}{\tilde{m}} \right)^2 \tan\beta, \quad (11)$$

where \tilde{m} stands for the heaviest sparticle mass in the loop. The effect has been noticed and emphasized by the earlier studies focusing on the muon anomalous magnetic moment in the context of the MSSM [8].

Relation (11) predicts a very simple $\tan\beta$ dependence. It suggests that the large $\tan\beta$ regime of the MSSM may already be constrained by the currently allowed window, eq.(5). That is of interest for models of grand unification based on simple SO(10), since the SO(10) GUT constraint $y_t = y_b = y_\tau$ for the Yukawa couplings of the third generation implies $\tan\beta \approx 50$. In this study, we first apply our analysis to the MSSM constrained only by gauge coupling unification and, as a warm-up, compute the muon anomalous magnetic moment for fixed values $\tan\beta = 2$ and $\tan\beta = 20$. Next, we proceed to the best fits of a simple SO(10) SUSY GUT [9]. We present our results in terms of the contour lines of constant a_μ^{SUSY} drawn in the SUSY parameter space. In section 2, we review our numerical analysis. Sections 3 and 4 discuss the results and prospects for the future.

2 Numerical Analysis

Our numerical analysis has relied on the top down global analysis introduced in [5]. The soft SUSY breaking mediated by supergravity (SUGRA)[10] was assumed throughout this paper. As explained at the end of the previous section, the magnitude of $\tan\beta$ is of special interest for the analysis. Hence we discuss separately three cases with low, medium, and large value of $\tan\beta$. First, fixed $\tan\beta = 2$ was considered, along with the scalar trilinear parameter A_0 set to zero to simplify the analysis which is insensitive to A_0 in this case. Next, $\tan\beta$ was raised to 20 and A_0 set free to vary. In the third case, we used the results of the global analysis of model 4c, a simple SO(10) model with minimal number of effective operators leading to realistic Yukawa matrices. The model was suggested by Lucas and Raby [9] and its low-energy analysis was presented in [5]. A direct model dependence of a_μ on the details of the Yukawa matrices is, however, very limited. In this case, $\tan\beta$ was not fixed to any particular value. Instead, it was a free parameter of the global analysis but since the model predicted exact $t - b - \tau$ Yukawa coupling unification, the best fit values of $\tan\beta$ were always found between 50 and 55, dependent on a particular $(m_0, M_{1/2})$ point as explained below. A_0 was free to vary — as for $\tan\beta = 20$ — which allowed the best fits to optimize the effects of the left-right stop mixing, which is enhanced by $\tan\beta$, in the analysis.

In each of the three cases, gauge coupling unification was imposed up to a small (less than 5%) negative correction, called ϵ_3 , to α_s at the unification scale M_G . Scale M_G has

been defined as the scale where α_1 and α_2 are exactly equal to the common value α_G . For low and medium $\tan\beta$ (2 and 20), the minimal set of the initial SUSY parameters

$$M_{1/2}, m_0, A_0, \text{sign}\mu, \text{ and } \tan\beta \quad (12)$$

was assumed, with $M_{1/2}$, m_0 , and A_0 (the universal gaugino mass, scalar mass and trilinear coupling) introduced at M_G . The Yukawa couplings of the third generation fermions at M_G were unconstrained and free to vary independently on each other. For large $\tan\beta$ in the third case, the scalar Higgs masses were allowed to deviate from m_0 in order to alleviate strong fine-tuning required for the correct electroweak symmetry breaking. Thus instead of (12), the set

$$M_{1/2}, m_0, (m_{H_d}/m_0)^2, (m_{H_u}/m_0)^2, A_0, \text{sign}\mu, \text{ and } \tan\beta \quad (13)$$

was actually used as initial SUSY parameters. As already mentioned, the third generation yukawas were strictly set equal to each other at M_G in this case. In fact, the SO(10)-based equality among them is the main reason why such a large $\tan\beta$ is attractive.

The rest of the analysis was then the same for each of the three cases. Particular values of m_0 and $M_{1/2}$ were picked up, while the rest of the initial parameters varied. That included varying α_G , M_G , ϵ_3 , the third generation Yukawa couplings, and A_0 (for medium and large $\tan\beta$). Using the 2-loop RGEs for the dimensionless couplings and 1-loop RGEs for the dimensionful couplings the theory was renormalized down to the SUSY scale, which was set equal to the mass of the Z boson. The electroweak symmetry breaking was checked to one loop as in [5], based on the effective potential method of ref.[11]. One-loop SUSY threshold corrections to fermion masses were calculated consistently at this scale. That is of particular importance for m_b which receives significant corrections if $\tan\beta$ is large. Also, the experimental constraints imposed by the observed branching ratio $BR(b \rightarrow s\gamma)$ and by direct sparticle searches were taken into account. Finally, $\delta a_\mu^{SUSY} \equiv \delta a_\mu^{\chi^+} + \delta a_\mu^{\chi^0}$ was evaluated following eqs.(7) and (8) for those values of the initial parameters which gave the lowest χ^2 calculated out of the ten low energy observables M_Z , M_W , ρ_{new} , $\alpha_s(M_Z)$, α , G_μ , M_t , $m_b(M_b)$, M_τ , and $BR(b \rightarrow s\gamma)$. Details of the low energy analysis can be found in [5]. The calculated value of δa_μ^{SUSY} did not have any effect on the χ^2 calculation and the subsequent selection of the SUSY parameter space.

3 Results and Discussion

The results for $\tan\beta = 2$ and $\tan\beta = 20$ are shown in figures 1–4. The figures 1 and 2 show the contour lines of constant $\delta a_\mu^{SUSY} \times 10^{10}$ in the $(m_0, M_{1/2})$ plane. These results are then transformed into the dependence on physical masses in figures 3 and 4, where we chose the $(m_{\tilde{\nu}}, m_{\chi^+})$ plane, with $m_{\tilde{\nu}}$ being the muon sneutrino mass and m_{χ^+} being the mass of the lighter chargino. The contour lines in these figures are bound from below by the limit on the neutralino mass (a limit $m_{\chi^0} > 55\text{GeV}$ was imposed flatly, for simplicity), and from above by the stau mass ($m_{\tilde{\tau}} > 60\text{GeV}$, in this analysis). The important observation is that the

present limits on δa_μ^{SUSY} , eq.(5) are not excluding any region of the parameter space which is left available by other experiments. The size of δa_μ^{SUSY} is in agreement with the results of Chattopadhyay and Nath, and of Moroi [8]. We can also confirm their observation that the neutralino contribution $\delta a_\mu^{\chi^0}$ is generally much smaller than the chargino contribution $\delta a_\mu^{\chi^\pm}$ in the whole parameter space available. Yet several interesting characteristics of the presented results cannot be read off directly from the earlier studies. It is first of all the simple pattern suggested by figures 3 and 4. The pattern in the figures shows a strong dependence of δa_μ^{SUSY} on the sneutrino mass and very little sensitivity to the mass of the lighter chargino. That can be understood from the fact that the loop integrals are in general most sensitive to the heaviest mass in the loop, and the universal initial conditions (see (12)) together with the experimental limits from direct searches always lead to $m_{\tilde{\nu}} \geq m_{\chi^\pm}$ at the electroweak scale. Actually, the figures show how well the approximate relation (11) works. One could *e.g.*, directly read out the value of sneutrino mass from a figure of this type once a more accurate measurement of a_μ and the value of $\tan\beta$ become available. Alternatively, a more accurate measurement of a_μ can be converted into a limit on $\tan\beta$ in a straightforward way, if the sneutrino mass is known. Also note how well the linear dependence $\delta a_\mu^{SUSY} \propto \tan\beta$ holds. If we overlapped figures 3 and 4, the contour lines marked as 10, 5, 2, 1, and 0.5 in figure 3 would be practically on top of the contour lines marked as 100, 50, 20, 10, and 5 in figure 4. That suggests that the $\tan\beta$ enhanced terms in eqs.(7) and (8) become dominant already for $\tan\beta \geq 2$. We checked this feature in the numerical analysis: typically, the term proportional to F_3 in eq.(7) accounts for about 80–85% of the net $\delta a_\mu^{\chi^\pm}$ for $\tan\beta = 2$, while it is 97-99% for $\tan\beta = 20$. (The analogous term in eq.(8) is less dominant, but has a smaller net effect since $\delta a_\mu^{\chi^0} < \delta a_\mu^{\chi^\pm}$.)

From these results one could extrapolate that the current a_μ limit, eq.(5), places an important constraint on the analysis if $\tan\beta$ is as large as 50.

However, case $\tan\beta \approx 50$ is qualitatively different. As discussed in the study by Blažek and Raby [5], the global analysis yields two distinct fits, figs. 5a–b. The fits differ by the sign of the Wilson coefficient C_7^{MSSM} in the effective quark Hamiltonian below the electroweak scale. (The coefficient C_7 determines the $b \rightarrow s\gamma$ decay amplitude, after the QCD renormalization effects are taken into account [12].) In the MSSM with large $\tan\beta$, the sign of C_7 can be the same, or the opposite, as in the SM. It can be reversed due to the fact that the chargino contribution can be of either sign. This contribution is enhanced by $\tan\beta$ compared to the SM and charged Higgs contributions, whose signs are fixed and alike, and thus the flipped sign of C_7^{MSSM} cannot be obtained for low $\tan\beta$.⁴ For $\tan\beta \approx 50$ the fit with the flipped sign is equally good as the fit with the sign unchanged, see figure 5. The fits differ in the range of the allowed SUSY parameter space: to reverse the sign the chargino contribution accepts lower squark masses and different values of A_0 than in the case when the sign is unchanged.

One can anticipate that these differences will be reflected in the analysis of δa_μ^{SUSY} with

⁴The contributions with neutralinos or gluinos in the loop always turn out to be small in our analysis.

$\tan\beta \approx 50$, since the quark sector is correlated with the lepton sector through the unification constraint, and the soft masses are interrelated through the universality assumption. Due to differences in SUSY spectra we can expect δa_μ^{SUSY} to be more significant in the fit with the flipped sign of C_7^{MSSM} than in the fit where the signs are the same. These expectations are indeed realized in our results in figs. 6a and 6b. In these figures, we plot the contour lines in the $(m_0, M_{1/2})$ plane of δa_μ^{SUSY} , calculated according to eqs. (7) and (8), with all the masses, mixings and couplings taken over from the best fit values at the specific $(m_0, M_{1/2})$ point in the SUSY space.⁵ The important feature, which runs contrary to the naive extrapolation from the previous two cases, is that the MSSM contribution to the muon anomalous magnetic moment *stays within the currently allowed range at 90% C.L., even for $\tan\beta$ as large as predicted by simple $SO(10)$ GUTs*. Despite the fact that figures 1-4 suggest that the analysis with $\tan\beta = 50 - 55$ becomes sensitive to the current constraint on a_μ , eq.(5), our results in fig.6 clearly indicate that this is not the case. The reason for this is that we consistently demand that all known particle physics constraints (besides those imposed by a_μ) are accounted for. For $\tan\beta$ as large as 50, the allowed SUSY parameter range is further reduced by strong constraints on the b quark mass and the branching ratio $BR(b \rightarrow s\gamma)$, when compared to the regime where $\tan\beta = 2$ or 20.

Finally, we make a note on the sign of μ . As clearly indicated on the top of each figure, we have presented our results just for $\mu > 0$. For this sign of the μ parameter, the SUSY contributions to a_μ are positive across the whole $(m_0, M_{1/2})$ plane. For $\mu < 0$, the contributions change sign too. However, the chargino contribution to C_7 also changes sign in this case, which leads to unacceptable values of $BR(b \rightarrow s\gamma)$ for medium and large $\tan\beta$. It is amazing to observe that for this range of $\tan\beta$ the sign of the μ parameter favored by $b \rightarrow s\gamma$ is the same as the sign preferred by the experimental window open for δa_μ^{NEW} .⁶

4 Prospects for the New BNL Experiment and Conclusions

When the future BNL experiment reduces the uncertainty on a_μ down to $\pm 12 \times 10^{-10}$ at 90% C.L., eq.(6), the muon anomalous magnetic moment will undoubtedly turn into a powerful constraint on the MSSM analysis. It is already clear from figures 1, 2, and 6 that it will be a major constraint for large and medium $\tan\beta$ in the region $m_0 < 400 - 500 \text{ GeV}$. Of

⁵We do not show plots in the $(m_{\tilde{\nu}}, m_{\chi^+})$ plane in this case. For large $\tan\beta$ the best fits of the global analysis result in the lightest chargino being higgsino-like, with its mass close to the electroweak scale across the whole $(m_0, M_{1/2})$ plane. Thus the two-dimensional plots in the $(m_{\tilde{\nu}}, m_{\chi^+})$ plane would contract to a dependence on $m_{\tilde{\nu}}$ only.

⁶For low $\tan\beta$, the $b \rightarrow s\gamma$ constraint disappears (the chargino contribution to C_7 is small) and μ can be negative. However, figure 1 shows that δa_μ^{SUSY} is very small in this case. We know from the earlier studies [8] that no substantial change in the magnitude of δa_μ^{SUSY} occurs for different signs of μ . Thus we conclude that for $\mu < 0$ only the low $\tan\beta$ case is viable, but then the SUSY contributions to a_μ stay below the electroweak contributions and will be hard to observe even after the E821 experiment is completed.

course, the BNL result may drastically affect the MSSM analysis with any value of $\tan\beta$ if the observed central value turns out to be below (or well above) the SM prediction. For such an outcome, the muon anomalous magnetic moment will actually become a dominant constraint for the MSSM analysis with the universal SUGRA-mediated SUSY breaking terms.

In the meantime, a_μ does not pose any new constraints on the MSSM analysis under the terms considered in this work.

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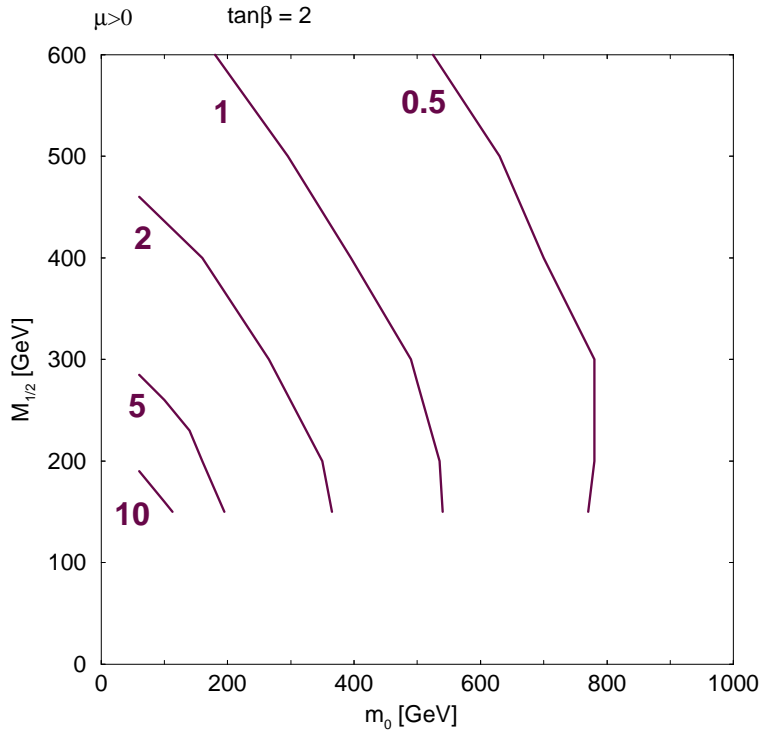


Figure 1: Contour lines of constant $\delta a_\mu^{SUSY} \times 10^{10}$ in the analysis with fixed $\tan\beta = 2$ in the SUSY parameter space.

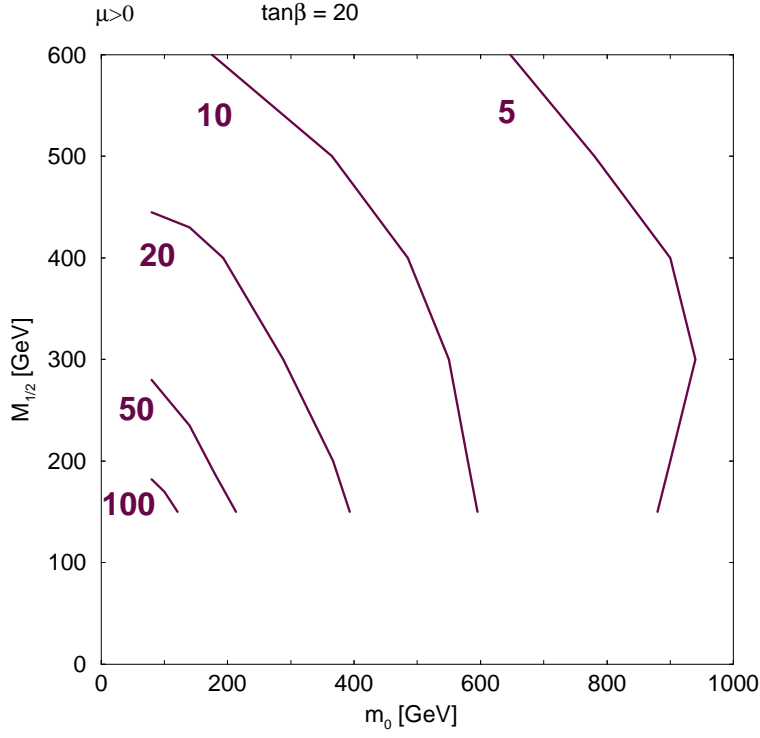


Figure 2: Contour lines of constant $\delta a_\mu^{SUSY} \times 10^{10}$ in the analysis with fixed $\tan\beta = 20$, in the SUSY parameter space.

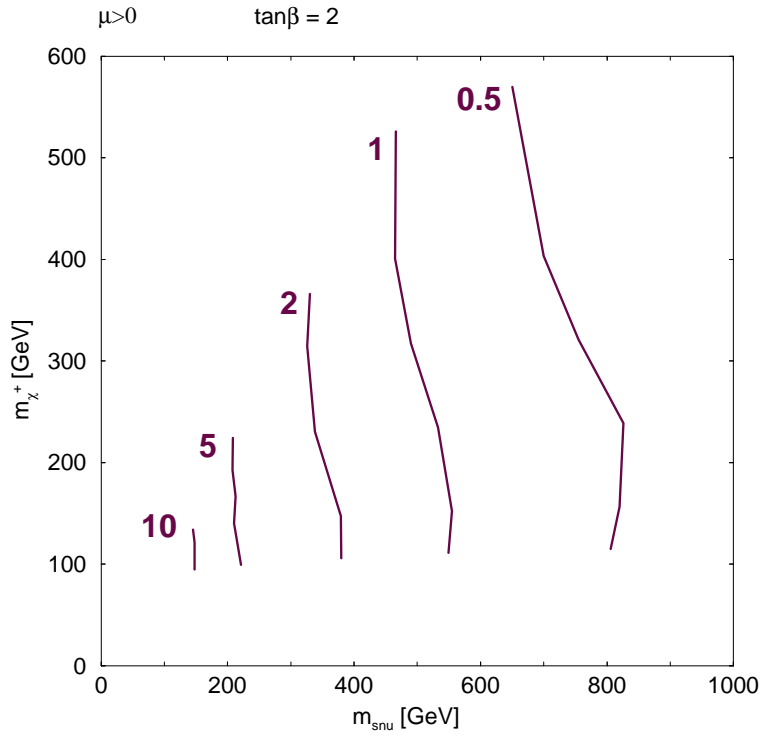


Figure 3: Contour lines of constant $\delta a_{\mu}^{SUSY} \times 10^{10}$ in the analysis with fixed $\tan\beta = 2$, in the $(m_{\tilde{\nu}}, m_{\chi^+})$ plane, where $m_{\tilde{\nu}}$ is the muon sneutrino mass and m_{χ^+} is the mass of the lighter chargino.

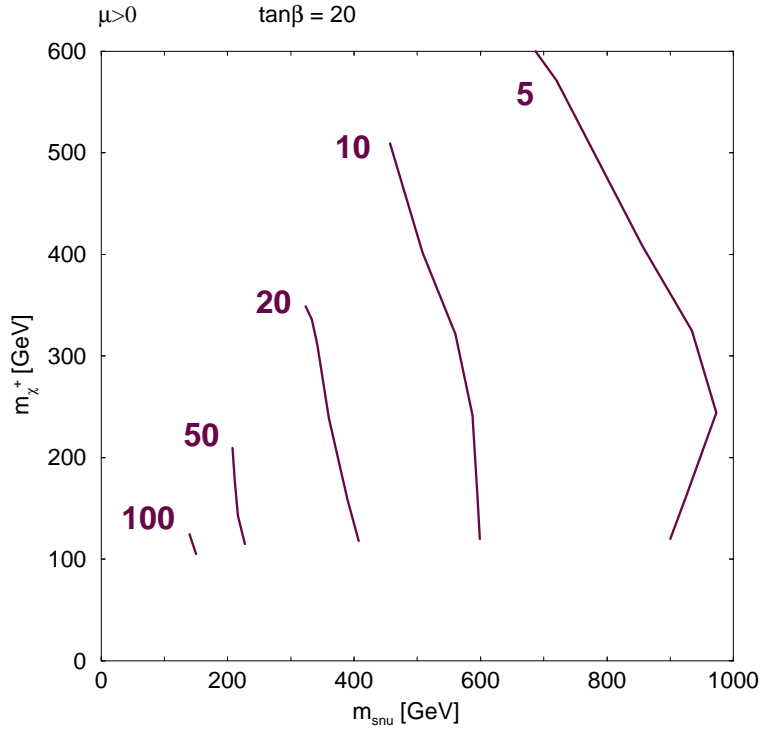


Figure 4: Contour lines of constant $\delta a_{\mu}^{SUSY} \times 10^{10}$ in the analysis with fixed $\tan\beta = 20$, in the $(m_{\tilde{\nu}}, m_{\chi^+})$ plane, where $m_{\tilde{\nu}}$ is the muon sneutrino mass and m_{χ^+} is the mass of the lighter chargino.

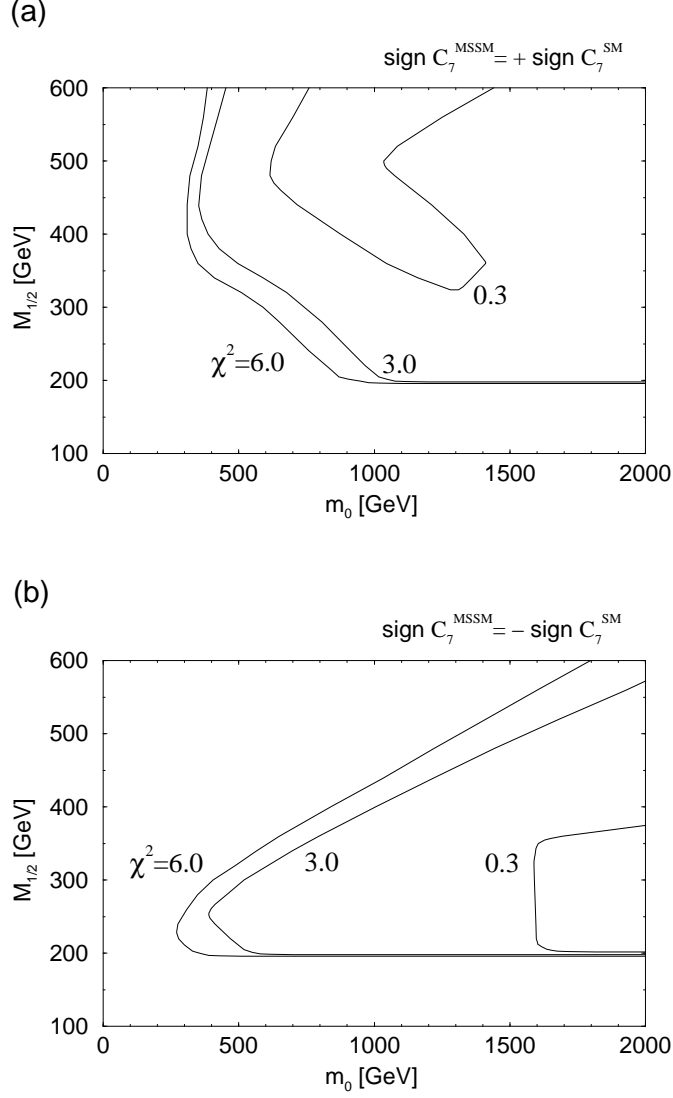


Figure 5: χ^2 contour plots in the best fits of a simple SO(10) model, with the Wilson coefficient C_7^{MSSM} (relevant for the $b \rightarrow s\gamma$ decay) of (a) the same (b) the opposite sign as compared to C_7^{SM} . As indicated, the contour lines correspond to $\chi^2 = 6, 3$, and 0.3 per 3 *d.o.f.*, respectively. $\tan\beta$ varies between 50 and 55 due to the model prediction that t , b , and τ Yukawa couplings are equal at the GUT scale.

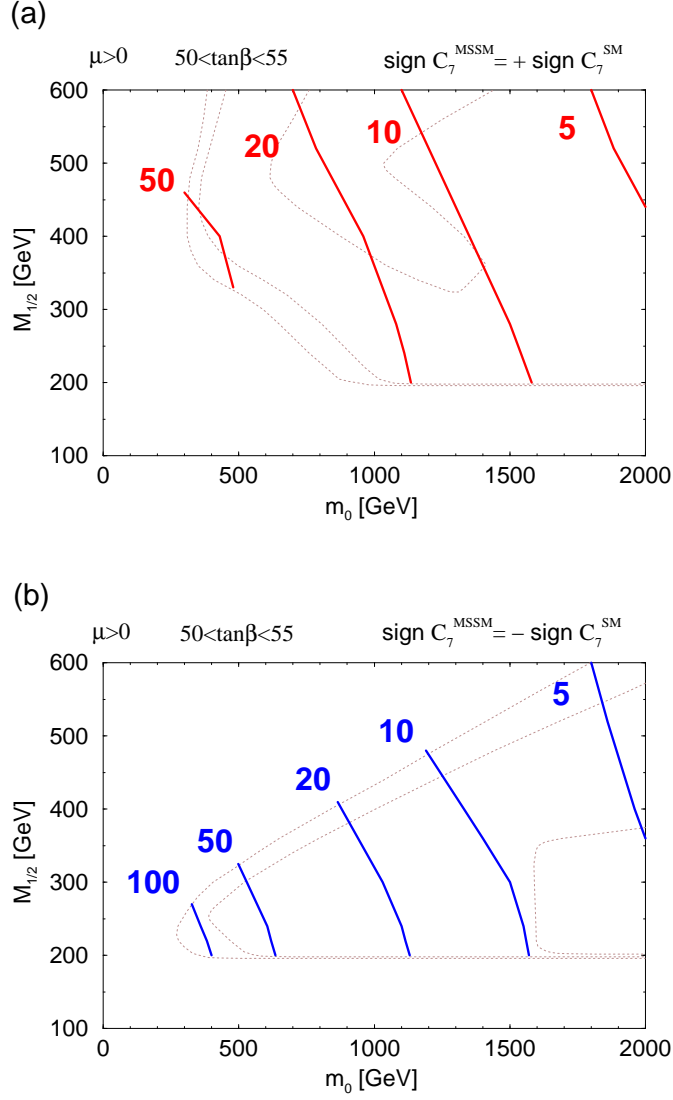


Figure 6: Contour lines of constant $\delta a_\mu^{\text{USY}} \times 10^{10}$ in the best fits of a simple SO(10) model, with the Wilson coefficient C_7^{MSSM} of (a) the same (b) the opposite sign as compared to C_7^{SM} . For better reference, the χ^2 contour lines of figures 5a and 5b are shown in the background of (a) and (b), respectively, as dotted lines.